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Reionization after *JWST*: a photon budget crisis?

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ABSTRACT

New *JWST* observations are revealing the first galaxies to be prolific producers of ionizing photons, which we argue gives rise to a tension between different probes of reionization. Over the last two decades, a consensus has emerged where star-forming galaxies are able to generate enough photons to drive reionization, given reasonable values for their number densities, ionizing efficiencies $\xi_{\rm ion}$ (per unit ultraviolet luminosity), and escape fractions $f_{\rm esc}$. However, some new *JWST* observations infer high values of $\xi_{\rm ion}$ during reionization and an enhanced abundance of earlier ($z \gtrsim 9$) galaxies, dramatically increasing the number of ionizing photons produced at high z. Simultaneously, recent low-z studies predict significant escape fractions for faint reionization-era galaxies. Put together, we show that the galaxies we have directly observed ($M_{\rm UV} < -15$) not only can drive reionization, but would end it too early. That is, our current galaxy observations, taken at face value, imply an excess of ionizing photons and thus a process of reionization in tension with the cosmic microwave background and Lyman-α forest. Considering galaxies down to $M_{\rm UV} \approx -11$, below current observational limits, only worsens this tension. We discuss possible avenues to resolve this photon budget crisis, including systematics in either theory or observations.

Key words: cosmology: theory – dark ages, reionization, first stars – diffuse radiation – galaxies: luminosity function, mass function.

1 INTRODUCTION

The epoch of reionization represents the last major phase transition of our Universe. During reionization, the intergalactic gas went from cold and neutral before the first cosmic structures formed (at redshift $z \sim 30$, or 100 Myr after the big bang) to hot and ionized by $z \sim 5$ (roughly a billion years later). While we are certain that this process took place, we do not know how. The likely culprits for reionization are the first star-forming galaxies (Robertson et al. 2015, hereafter R15), but other suspects include supermassive black holes (Madau & Haardt 2015; Madau et al. 2024), and even dark matter (Liu, Slatyer & Zavala 2016). More broadly, the timing and topology of reionization hold a treasure trove of information on the astrophysics of the early universe, which we have yet to uncover.

The accounting of reionization is rather simple: there have to be enough photons to ionize all the intergalactic hydrogen atoms, including their recombinations. During the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) era, this was a stringent requirement, as cosmic microwave background (CMB) data implied an approximate mid-point of reionization at $z = 10$–11 (Komatsu et al. 2011), earlier than expected from standard galaxy formation models and beyond the reach of contemporaneous direct observations. With the advent of the *Planck* satellite, this tension was eased, as newer CMB data preferred later reionization (with an effective $z \sim 7$–8; Ade et al. 2016), and by then *Hubble Space Telescope* (*HST*) observations had characterized a population of star-forming galaxies at those redshifts (Madau & Dickinson 2014). Together, these observations alleviated the demand for ionizing photons and quickly led to the consensus that, under reasonable assumptions, star-forming galaxies were able to drive reionization (Bouwens et al. 2015; R15; Finkelstein et al. 2019, hereafter F19). In this letter, we examine whether this consensus holds in light of recent *JWST* observations of the high-redshift universe.

Three key factors determine the average reionization history: the production rate of ionizing photons (by early galaxies and black holes), the fraction $f_{\rm esc}$ of those photons that escape to the intergalactic medium (IGM) and can ionize neutral hydrogen, and the number of recombinations per hydrogen atom. While there remain open questions about the last factor (Davies et al. 2021), the first two are particularly uncertain.

The production rate of ionizing photons is given by the early-galaxy abundance, usually expressed through the ultraviolet (UV) luminosity function (UVLF, the comoving number density of galaxies per UV magnitude), times the ionizing efficiency $\xi_{\rm ion}$ of each galaxy. Though there is broad agreement on the bright end of the UVLF, the number density of ultra-faint (below $M_{\rm UV} \approx -14$) galaxies is

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virtually unconstrained. Theoretically, we expect the UVLF to 'turn over' at some magnitude $M_{\rm UV}^{\rm turn}$ due to feedback (Shapiro, Iliev & Raga 2004), and *HST* observations have constrained this turnover to be fainter than $M_{\rm UV}^{\rm turn} \approx -15$ (Atek et al. 2018). At the same time, some new *JWST* observations are finding early galaxies to have higher ionizing efficiencies $\xi_{\rm ion}$ than canonically assumed [with $\log_{10}\xi_{\rm ion}/({\rm Hz\,erg^{-1}}) \approx 25.5$–$26.0$ versus 25.2; Curtis-Lake et al. 2023; Hsiao et al. 2023; Prieto-Lyon et al. 2023; Atek et al. 2024; Calabro et al. 2024; Endsley et al. 2024; Simmonds et al. 2024; though see Matthee et al. 2023; Meyer et al. 2024; Pahl et al. 2024]. Moreover, *JWST* is also unveiling an enhanced population of both star-forming galaxies at $z \gtrsim 9$ (Castellano et al. 2022; Eisenstein et al. 2023; Finkelstein et al. 2023, 2024; Harikane et al. 2023), with an unknown origin (Ferrara, Pallottini & Dayal 2023; Mason, Trenti & Treu 2023; Mirocha & Furlanetto 2023; Muñoz et al. 2023), and supermassive black holes (Matthee et al. 2024) that are likely obscured (Greene et al. 2024), which would further boost the ionizing-photon budget. Such a wealth of photons will accelerate the process of reionization, if they escape their host galaxies.

The escape fraction $f_{\rm esc}$ of early galaxies is a contentious topic. The basic problem is that the ionizing-photon production is dominated by very massive, short-lived stars, which may live and die before their birth clouds are dispersed, minimizing photon escape. The Binary Population and Spectral Synthesis models (BPASS, Eldridge & Stanway 2009) provided a new hope for high escape fractions, as binary interactions help to lengthen effective stellar lifetime and so boost the effective $f_{\rm esc}$. Models in which the escape fraction is set by local, cloud-scale physics suggest that $f_{\rm esc}$ could be independent of galaxy properties such as mass or luminosity (Ma et al. 2016). However, different simulations predict $f_{\rm esc}$ growing for brighter galaxies (Sharma et al. 2016), declining (Kimm & Cen 2014; Wise et al. 2014), or peaking at intermediate masses (e.g. Ma et al. 2020; Yoo, Kimm & Rosdahl 2020; Rosdahl et al. 2022; Yeh et al. 2023). From a theoretical perspective, there seems to be no clear consensus on the nature of $f_{\rm esc}$ in high-z galaxies. Observationally, it is extremely challenging to measure $f_{\rm esc}$ while there is neutral hydrogen in the IGM. However, recent studies of low-z analogues of reionization-era galaxies have found a strong correlation between their escape fractions and UV slopes $\beta_{\rm UV}$: bluer galaxies exhibit larger values of $f_{\rm esc}$ (Begley et al. 2022; Chisholm et al. 2022; Flury et al. 2022; Saldana-Lopez et al. 2023). *JWST* and *HST* data show that early galaxies have bluer slopes than their average low-z counterparts (e.g. Topping et al. 2022; Cullen et al. 2023; Weibel et al. 2024), such that the few studies of reionization-era galaxies indicate modest $f_{\rm esc}$ values near 5–15 per cent (Mascia et al. 2023; Lin et al. 2024).

Here, we argue that combining the abundance of directly observed reionization-era galaxies, the new *JWST* estimates of $\xi_{\rm ion}$, and the low-z insights on $f_{\rm esc}$ leads to too many ionizing photons at high redshifts, ending reionization too early. Such an early reionization is in contradiction with current CMB (Aghanim et al. 2020) and Lyman-α forest observations (Bosman et al. 2022), and poses *a tension in the photon budget during reionization*. We will outline possible ways to ease this tension, including physical ingredients missing in our theoretical models, interpretation of observations, or both.

Through this letter, we assume a flat Lambda cold dark matter (ΛCDM) cosmology with $h = 0.7$ and $\Omega_{\rm M} = 0.3$ to match that assumed in Bouwens et al. (2021) and Donnan et al. (2024); all magnitudes are AB (Oke & Gunn 1983), and quantities are spatially averaged unless otherwise indicated.

2 MODELLING REIONIZATION

We will follow a simple model of reionization to solve for the volume-averaged hydrogen neutral fraction $x_{\rm H\,I} \equiv n_{\rm H\,I}/n_{\rm H}$, and its complement the ionized fraction $x_{\rm H\,II} \equiv 1 - x_{\rm H\,I}$. This quantity evolves as (Madau, Haardt & Rees 1999)

$$\dot{x}_{\rm H\,II} = \frac{\dot{n}_{\rm ion}}{n_{\rm H}} - \frac{x_{\rm H\,II}}{t_{\rm rec}}, \tag{1}$$

which showcases the competition between the 'sources' (first term) and 'sinks' (second term) of ionizing photons. The former is given by the density of ionizing photons produced ($\dot{n}_{\rm ion}$) divided by that of hydrogen $n_{\rm H} = \rho_{\rm b}(1 - Y_{\rm He})/m_{\rm H}$, where $Y_{\rm He}$ is the helium mass fraction, $m_{\rm H}$ is the proton mass, and $\rho_{\rm b}$ is the baryon energy density, which scales as $(1+z)^3$. The sink term captures the number of recombinations that hydrogen atoms suffer on average, characterized by a time-scale (Shull et al. 2012)

$$t_{\rm rec} = [C\,\alpha_{\rm B}(1 + x_{\rm He})n_{\rm H}]^{-1}\,, \tag{2}$$

where $x_{\rm He} \equiv n_{\rm He}/n_{\rm H} \approx Y_{\rm He}/[4(1 - Y_{\rm He})]$, $\alpha_{\rm B}$ is the case B recombination coefficient, and C is the clumping factor. The clumping factor is difficult to estimate theoretically, as it depends on how ionized regions penetrate into high-density clumps. Simulations predict $C \approx 2$–5 during reionization, growing towards lower z (e.g. Pawlik, Schaye & Vecchia 2015). Recent work in Davies et al. (2021) instead suggests that more recombinations are needed to explain the short mean free path of ionizing photons at $z \sim 6$ (thanks to absorption by pervasive high-density clumps known as Lyman-limit systems; Becker et al. 2021; Zhu et al. 2023). For simplicity and comparison with past literature (R15), we will set $C = 3$ and evaluate $\alpha_{\rm B}$ at $T = 2 \times 10^4$ K for now [which yields nearly identical results to using the $C(z)$ fit from Shull et al. (2012)], and return to the effect of recombinations later.

For reionization to progress, the sources have to win over the sinks. Our sources will be star-forming galaxies, which produce a background of ionizing photons at a rate of

$$\dot{n}_{\rm ion} = \int {\rm d}M_{\rm UV}\,\Phi_{\rm UV}\,\dot{N}_{\rm ion}\,f_{\rm esc}, \tag{3}$$

where all factors inside the integral are assumed to depend on $M_{\rm UV}$, and we integrate down to a cut-off magnitude $M_{\rm UV}^{\rm ion.\,cut\text{-}off}$ that will be a free parameter. Here, $\Phi_{\rm UV}$ is the UVLF, taken at $z \leq 9$ from the pre-*JWST* fit in Bouwens et al. (2021) and at $z > 9$ from the *JWST* calibrations of Donnan et al. (2024) [see Appendix A in the supporting information for alternative analyses using only pre-*JWST* UVLFs, including that of Finkelstein & Bagley (2022)], and $\dot{N}_{\rm ion} \equiv L_{\rm UV}\,\xi_{\rm ion}$ is the production rate of ionizing photons per galaxy, given by their UV luminosity $L_{\rm UV}$ times the ionizing efficiency $\xi_{\rm ion}$, of which a fraction $f_{\rm esc}$ escapes into the IGM.

It is apparent that the product $\xi_{\rm ion} \times f_{\rm esc}$ will determine the timing of reionization, and that these two factors are, at face value, fully degenerate. Increasing $\xi_{\rm ion}$ per galaxy while decreasing $f_{\rm esc}$ will yield identical effects on the IGM. Fortunately, though, direct Balmer-line observations can be used to tease out the amount of ionizations in the galaxy, and thus the amount of non-escaping ionizing photons $\xi_{\rm ion}(1 - f_{\rm esc})$. Using the Robertson et al. (2013) inference[1] of $\log_{10}\xi_{\rm ion} = 25.2$ Hz erg^{-1} (though see Bouwens et al. 2016; De Barros et al. 2019; Lam et al. 2019, for higher reported values), R15 showed that $f_{\rm esc} = 20$ per cent is sufficient if galaxies

[1]We will assume $f_{\rm esc} = 0$ in all inferences of $\xi_{\rm ion}$, which conservatively underestimates the production of ionizing photons.

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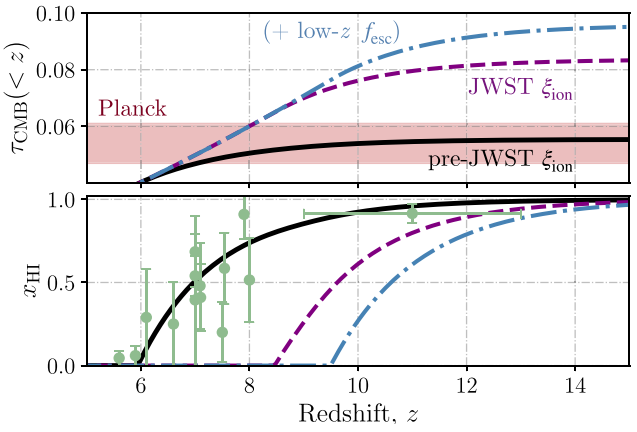

Figure 1. The new *JWST* and low-z observations imply an earlier reionization, in tension with the CMB. *Bottom*: Evolution of the neutral fraction $x_{\rm H\,I}$ as a function of redshift z for a pre-*JWST* model (black solid lines, with a cut-off at $M_{\rm UV} = -13$ and $f_{\rm esc} = 0.2$, following R15), for the same model but with a *JWST*-calibrated $\xi_{\rm ion}$ (purple dashed lines, following Simmonds et al. 2024), and a model where in addition $f_{\rm esc}$ is determined from low-z analogues (blue dot–dashed lines, using the fit in Chisholm et al. 2022). Green points show a collection of observational constraints from McGreer, Mesinger & D'Odorico (2015), Greig et al. (2017), Greig, Mesinger & Bañados (2019), Sobacchi & Mesinger (2015), Mason et al. (2019), Whitler et al. (2020), Wang et al. (2020), and Nakane et al. (2024) (see also Bruton et al. 2023). *Top*: CMB optical depth $\tau_{\rm CMB}$, where the red band is the measurement from Aghanim et al. (2020). The new galaxy observations give rise to far more ionizing photons, and at face value are in severe tension with CMB data.

down to $0.001L_\star$ ($M_{\rm UV}^{\rm ion.\,cut\text{-}off} \approx -13$) contribute to reionization. We illustrate what reionization would look like for this pre-*JWST* calibrated model in Fig. 1. It is over by $z \sim 6$ and produces an optical depth $\tau_{\rm CMB} \approx 0.055$, bringing galaxy observations into agreement with *Planck* CMB measurements.

The arrival of *JWST* is opening a new window to reionization. Observations from different teams are finding large values of $\xi_{\rm ion}$, in some cases growing towards higher redshifts and fainter galaxies [though see Endsley et al. (2024) where $\xi_{\rm ion}$ is still high but grows towards the bright end instead, we study this case in Appendix A in the supporting information]. In particular, Simmonds et al. (2024) find a consistent increase in $\xi_{\rm ion}$ up to $z = 9$ and $M_{\rm UV} = -16.5$ (where we will conservatively cap $\xi_{\rm ion}$ to avoid extrapolation), well fitted by

$$\log_{10}\left[\xi_{\rm ion}/({\rm Hz\,erg^{-1}})\right] \approx 25.8 + 0.11(M_{\rm UV} + 17) + 0.05(z - 7). \tag{4}$$

Such faint, early galaxies will produce ∼4 times more ionizing photons than expected pre-*JWST* (Atek et al. 2024, implying a very young stellar population). The purple line in Fig. 1 shows how reionization would progress assuming this *JWST*-calibrated $\xi_{\rm ion}$, while keeping everything else the same. In this case, the additional photons would kick-start reionization by $z \sim 12$ and finish it by $z \sim 8$, far overproducing the CMB optical depth ($\tau_{\rm CMB} \approx 0.08$) when compared to observations. Here, we have kept $f_{\rm esc} = 0.2$ as in R15, so the astute reader may wonder whether newer inferences of the escape fraction delay reionization.

We do not have a direct handle on $f_{\rm esc}$ during reionization, as escaping ionizing photons will be absorbed by the neutral IGM before reaching us. However, detailed studies of low-z analogues find a strong correlation, with significant scatter, between the far-UV (FUV) continuum slopes $\beta_{\rm UV}$ of galaxies and their Lyman-continuum (LyC) escape fractions. This is physically explained by the dust along the line of sight simultaneously attenuating the FUV stellar continuum and the ionizing photons. We will use the fit from Chisholm et al. (2022), calibrated on the $z \sim 0$ low-z Lyman continuum survey [LzLCS, Flury et al. 2022; see Trebitsch et al. (2022) for an implementation on reionization], where

$$f_{\rm esc} = A_f \times 10^{b_f \beta_{\rm UV}}, \tag{5}$$

with $A_f = 1.3 \times 10^{-4}$ and $b_f = -1.22$. In this relation, galaxies that are bluer have less dust and low-ionization gas along the line of sight, and thus fewer sinks of ionizing photons. This correlation is similarly observed at $z \sim 3$ in different surveys (Steidel et al. 2018; Pahl et al. 2021; Begley et al. 2022; Saldana-Lopez et al. 2023). We can then employ the $f_{\rm esc}$–$\beta_{\rm UV}$ relation, with the $\beta_{\rm UV}$–$M_{\rm UV}$ measurements from Zhao & Furlanetto (2024), which incorporates both *JWST* and *HST* measurements from Bouwens et al. (2014), Topping et al. (2022), and Cullen et al. (2023), to predict[2] $f_{\rm esc}(M_{\rm UV})$. Note that here, and throughout the text, we cap the UV slopes at $\beta_{\rm UV} = -2.7$ when computing $f_{\rm esc}$ to avoid extrapolation in this relation (though we implicitly extrapolate in z and $M_{\rm UV}$, see Table A1 in the supporting information), as that corresponds to the bluest galaxies where equation (5) is calibrated. We show the result of applying this calibration as the blue line in Fig. 1. The *JWST*-calibrated $\xi_{\rm ion}$ multiplied by $f_{\rm esc}$ (inferred using the high-z $\beta_{\rm UV}$–$M_{\rm UV}$ and low-z $f_{\rm esc}$–$\beta_{\rm UV}$ relations) produces an even earlier reionization, and consequently even more tension with $\tau_{\rm CMB}$.

The curves shown in Fig. 1 are meant to illustrate the impact of the new $\xi_{\rm ion}$ and $f_{\rm esc}$ results for a particular reionization model. Let us now move to perform a more detailed study, where we vary different underlying assumptions and compare against current observations.

3 OBSERVATIONAL CONSTRAINTS

To understand reionization, we need to know the ionizing-photon budget, i.e. how many photons are produced and what fraction escape their galaxies. We model the former by taking the ionizing efficiency $\xi_{\rm ion}$ from equation (4), as measured in *JWST* observations, and integrating the UVLF down to a cut-off magnitude $M_{\rm UV}^{\rm ion.\,cut\text{-}off}$ (below where we will assume that galaxies do not emit ionizing photons efficiently, because $f_{\rm esc}$, $\xi_{\rm ion}$, or the UVLF itself go to zero, see Appendix B in the supporting information for an example). For the latter, we define the ionization-averaged escape fraction as

$$\langle f_{\rm esc}\rangle_{\rm ion.} \equiv \frac{\dot{n}_{\rm ion}(f_{\rm esc})}{\dot{n}_{\rm ion}(f_{\rm esc} = 1)}, \tag{6}$$

with $\dot{n}_{\rm ion}$ defined in equation (3). These two free parameters, $M_{\rm UV}^{\rm ion.\,cut\text{-}off}$ and $\langle f_{\rm esc}\rangle_{\rm ion.}$, encapsulate our uncertainty about the impact of high-z galaxies on reionization. They must obey three different observational constraints.

First, the cut-off $M_{\rm UV}^{\rm ion.\,cut\text{-}off}$ has to be fainter than –15 (Atek et al. 2018), given current *HST* and *JWST* observations, which we show as a green band in Fig. 2. Secondly, $\langle f_{\rm esc}\rangle_{\rm ion.}$ should follow the constraints derived from low-z analogues, shown as a blue band [using equation 5 with the best-fitting amplitude and error from the LzLCS survey of $z \sim 0$ galaxies (Chisholm et al. 2022), see Fig. A1 in the supporting information for the $z \sim 3$ sample from VANDELS of Saldana-Lopez

[2]Note that $\langle f_{\rm esc}\rangle(M_{\rm UV}) \equiv \int {\rm d}\beta_{\rm UV}\, P(\beta_{\rm UV}|M_{\rm UV}) f_{\rm esc}(\beta_{\rm UV})$, where $P(\beta_{\rm UV}|M_{\rm UV})$ can be approximated as a Gaussian with width $\sigma_\beta = 0.34$ (Smit et al. 2012), which makes $\langle f_{\rm esc}(\beta_{\rm UV})\rangle$ larger than $f_{\rm esc}(\langle\beta_{\rm UV}\rangle)$ by a factor of $\exp\left[(b_f \ln[10]\sigma_\beta)^2/2\right] \approx 1.1$–$1.5$.

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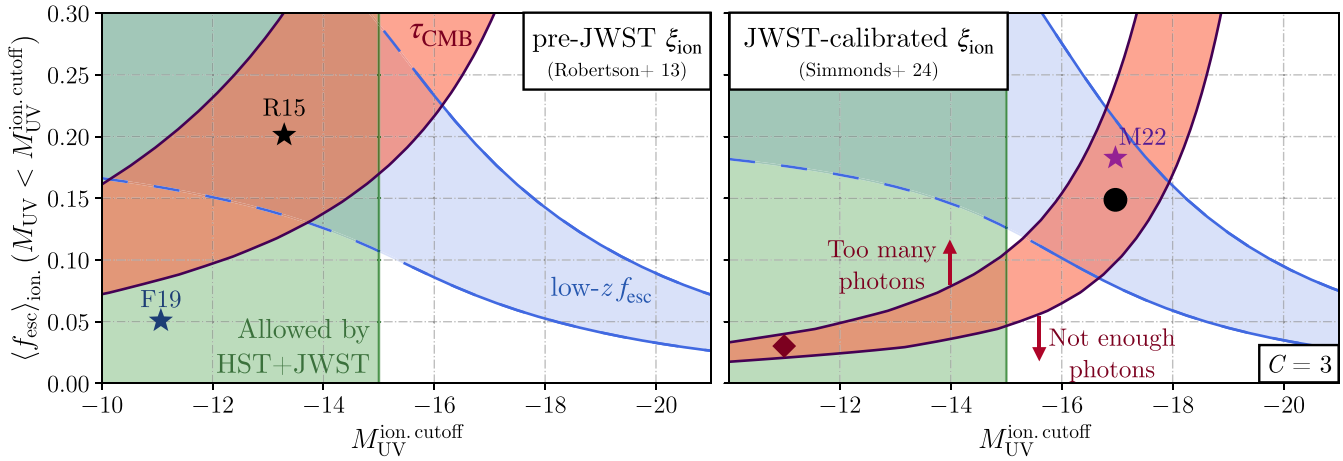

Figure 2. Tension in our models of reionization, expressed through the effective cut-off $M_{\rm UV}^{\rm ion.\ cut\text{-}off}$ on the UVLF (at which galaxies cease to emit ionizing photons), and the average escape fraction $\langle f_{\rm esc}\rangle_{\rm ion.}$ above that cut-off. The three coloured contours correspond to the regions allowed by the CMB optical depth $\tau_{\rm CMB}$ (red), the low-z $f_{\rm esc}$ studies (blue), and direct *HST* + *JWST* observations of no cut-off down to $M_{\rm UV} \approx -15$ (green). The *left* panel assumes a pre-*JWST* value of $\xi_{\rm ion}$ from Robertson et al. (2013), where the three coloured regions nicely overlap for faint cut-offs and $f_{\rm esc} \approx 0.2$. The *right* panel instead takes the new *JWST*$\xi_{\rm ion}$ calibration from Simmonds et al. (2024), in which case the three regions do not overlap, showing a tension in reionization. In more detail, the blue region follows the results from the LzLCS survey of reionization-era analogues (Chisholm et al. 2022), evaluated at $z = 7$, with solid lines corresponding to the $M_{\rm UV}$ directly observed, and dashed lines to extrapolation, in all cases capping UV slopes at $\beta_{\rm UV} = -2.7$. We highlight three popular pre-*JWST* models from R15, F19, and M22 (the last one assumes a larger $\xi_{\rm ion}$ closer to the new *JWST* value) as coloured stars. The red diamond and black circle on the right panel correspond to possible solutions to the tension (further explored in Fig. 3), which are in conflict with either the $f_{\rm esc}$ or $M_{\rm UV}^{\rm ion.\ cut\text{-}off}$ constraints.

et al. (2023)]. Finally, the combination of $M_{\rm UV}^{\rm ion.\ cut\text{-}off}$ and $\langle f_{\rm esc}\rangle_{\rm ion.}$ has to produce the correct reionization history, which we parametrize through the CMB optical depth[3]

$$\tau_{\rm CMB} = \int {\rm d}\ell n_{\rm e}\sigma_{\rm T}, \tag{7}$$

where ℓ is proper distance, $\sigma_{\rm T}$ is the Thomson cross-section, and $n_{\rm e}$ is the physical (not comoving) electron density, computed assuming that He I reionization tracks H I, and that He II reionization takes place at $z = 4$. The regions of parameter space that predict the correct $\tau_{\rm CMB}$ within 1σ are shown as red bands in Fig. 2. In the CMB bands, a brighter cut-off $M_{\rm UV}^{\rm ion.\ cut\text{-}off}$ requires higher values of $\langle f_{\rm esc}\rangle_{\rm ion.}$ to compensate the missing star formation – and subsequent photon production – at the faint end.

Fig. 2 showcases the tension between these three observations. The left panel shows the pre-*JWST* situation, where the lower $\xi_{\rm ion}$ allowed the three observational bounds (red, blue, and green regions) to overlap over a broad swath of parameter space fainter than $M_{\rm UV}^{\rm ion.\ cut\text{-}off} \approx -15$, with $f_{\rm esc} \approx 15$–30 per cent. The right panel, updated with the recent *JWST* observations, shows no overlap between the three. In this case, the requirements from $\tau_{\rm CMB}$ (red) and the low-z $f_{\rm esc}$ studies (blue) only overlap for cut-offs brighter than $M_{\rm UV}^{\rm ion.\ cut\text{-}off} \approx -15$ (outside of the green region, and thus disfavoured by direct *HST* + *JWST* observations). In other words, the new *JWST* observations imply an overproduction of photons during reionization, which would end this process earlier than allowed by the CMB. Note that the galaxies observed by *JWST* ($M_{\rm UV} \lesssim -15$) already produce too many photons, including fainter objects would only worsen this tension.

Fig. 2 also shows the parameter space of three popular reionization models: R15 ($\langle f_{\rm esc}\rangle_{\rm ion.} = 0.2$ and $M_{\rm UV}^{\rm ion.\ cut\text{-}off} \approx -13$), F19 (their best fit is at $\langle f_{\rm esc}\rangle_{\rm ion.} \approx 0.05$ and $M_{\rm UV}^{\rm ion.\ cut\text{-}off} \approx -11$), and the Lyman-$\alpha$ emitter (LAE) model of Matthee et al. (2022, hereafter M22), which we approximate as having $\langle f_{\rm esc}\rangle_{\rm ion.} = 0.17$ for galaxies down to $M_{\rm UV}^{\rm ion.\ cut\text{-}off} = -17$. Each of these models was calibrated to give rise to the correct $\tau_{\rm CMB}$, though with different $\xi_{\rm ion}$ assumptions. R15 assumed $\log_{10}\xi_{\rm ion} \approx 25.2$ Hz erg^{-1}, F19 fit for a somewhat higher z-dependent value, whereas M22 used a larger $\log_{10}\xi_{\rm ion} \approx 25.8$ Hz erg^{-1}, calibrated to low-z LAEs (Naidu et al. 2022). Each of these models is at odds with one of the three observational constraints, and thus outside one of the colour bands in Fig. 2, $\tau_{\rm CMB}$ (R15, outside red band), $f_{\rm esc}$ (F19, blue), or $M_{\rm UV}^{\rm ion.\ cut\text{-}off}$ (M22, green). As such, they illustrate three possible avenues to reduce the photon budget during reionization and reconcile galaxy and CMB observations.

4 POSSIBLE OUTS

Let us now discuss possible physical mechanisms that may resolve this apparent photon budget crisis.

(i) Perhaps some of the new $\xi_{\rm ion}$ calibrations are biased? It is possible that photometry alone cannot reliably recover $\xi_{\rm ion}$, that dust produces a systematic shift in this quantity (Shivaei et al. 2018), or that the *JWST* samples used to infer $\xi_{\rm ion}$ are not representative of the high-z galaxy population (if they are biased towards efficient ionizers or preferentially target galaxies in a burst). For example, the sample in Simmonds et al. (2024) is selected based on an emission-line flux cut in photometry, which could bias the sample towards strong line emitters (and thus high $\xi_{\rm ion}$) at fixed UV magnitude. We have repeated our analysis with a lower fixed $\xi_{\rm ion} = 10^{25.5}$ Hz erg^{-1} [in line with the lowest mean values reported in Endsley et al. (2024), which did not make an emission-line selection, as well as the $z > 4$ mean in Pahl et al. (2024), though see e.g. Matthee et al. (2023) for lower values], finding that this still requires a cut-off at $M_{\rm UV} \approx -14$ or brighter (see Fig. A1 in Appendix A in the supporting information). An alternative solution involves keeping a high $\xi_{\rm ion}$ on average but cutting off photon production for faint galaxies (either smoothly or setting $\xi_{\rm ion} \to 0$ below a cut-off magnitude $M_{\rm UV}^{\rm ion.\ cut\text{-}off}$). Fig. 3 shows that a

[3]We do not include measurements of $x_{\rm H\,I}(z)$ as a constraint, but will see that the models that predict the right $\tau_{\rm CMB}$ broadly agree with them.

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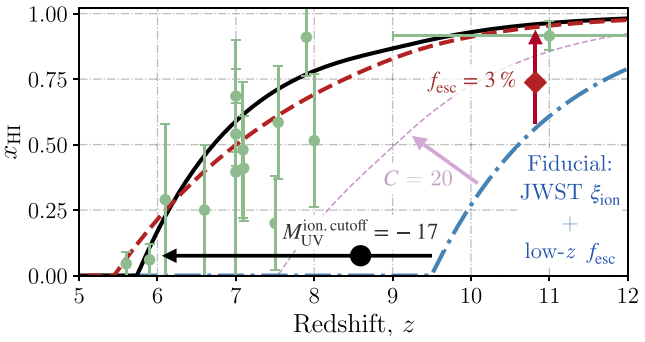

Figure 3. Possible solutions to the photon budget crisis, and how they would affect the timing of reionization. The blue dot–dashed line corresponds to our current understanding of reionization, as in Fig. 1. The pink dotted line assumes a higher clumping factor $C = 20$, which still does not produce enough recombinations. The red dashed line has $M_{\rm UV}^{\rm ion.\,cut\text{-}off} = -11$ and a low $f_{\rm esc} = 3$ per cent, whereas the black solid line posits $M_{\rm UV}^{\rm ion.\,cut\text{-}off} = -17$ with a larger $f_{\rm esc} = 15$ per cent. These two models produce the correct $\tau_{\rm CMB}$, but disagree with one of the two galaxy observations, as indicated by the red diamond and black circle in the right panel of Fig. 2. Their reionization histories $x_{\rm H\,I}(z)$ are potentially distinguishable from one another (measurements in green, which have not been used to calibrate the models).

$\xi_{\rm ion}$ cut-off at $M_{\rm UV}^{\rm ion.\,cut\text{-}off} = -17$ would be able to solve the tension. Such a cut-off would, however, be in conflict with the detections of ionizing photons down to $M_{\rm UV} \approx -15$ from Atek et al. (2024) and Prieto-Lyon et al. (2023), and down to $M_{\rm UV} \approx -16.5$ for the more statistically robust samples of Simmonds et al. (2024) and Endsley et al. (2024). Further *JWST* observations of high-z galaxies will be able to determine the $\xi_{\rm ion}$ distribution down to faint magnitudes and pinpoint the impact of burstiness on this quantity.

(ii) Maybe $f_{\rm esc}$ is far lower than expected? From Fig. 2, it is apparent that little to no extrapolation of the LzLCS relation to bluer galaxies is required to overproduce reionization (see also Appendix B in the supporting information). One possibility is that the low-z analogues in both LzLCS and VANDELS are biased (e.g. they may be more likely to be leakers), or that different mechanisms set $f_{\rm esc}$ at high and low redshifts (so that $f_{\rm esc}$ may not correlate well with $\beta_{\rm UV}$ at high z). Many of the LzLCS properties match those observed at high redshift (Tang et al. 2023), but it is possible (perhaps likely) that high-redshift galaxies have larger neutral gas fractions and lower dust-to-gas ratios than the low-redshift benchmarks (Heintz et al. 2024). This could lead to significantly lower $f_{\rm esc}$ at fixed $\beta_{\rm UV}$, or a turnaround towards fainter/bluer galaxies. While plausible, this $f_{\rm esc}$–$\beta_{\rm UV}$ redshift evolution is not observed in $z \sim 3$ galaxies, which in fact appear to have larger $f_{\rm esc}$ at fixed $\beta_{\rm UV}$ (Pahl et al. 2021; Saldana-Lopez et al. 2023). Another possibility is that there is a covariance between $f_{\rm esc}$ and $\xi_{\rm ion}$, such that galaxies that produce large amounts of ionizing photons have lower $f_{\rm esc}$. This has been predicted by simulations (Rosdahl et al. 2022), though Tang et al. (2019) and Naidu et al. (2022) observe the opposite trend in line emitters.

If one wanted to integrate the UVLF down to the theoretically expected cut-off at $M_{\rm UV} \approx -11$ (Kuhlen & Faucher-Giguere 2012), the $f_{\rm esc}$ needed to fit $\tau_{\rm CMB}$ is $\langle f_{\rm esc} \rangle_{\rm ion.} \approx 3$ per cent, as shown in Fig. 3, slightly lower but comparable to F19. For such a low value, the LzLCS relationship would require $\beta_{\rm UV} \approx -1.93$, significantly redder than *JWST* has observed at $z > 5$ (Topping et al. 2022; Cullen et al. 2023). Moreover, even setting a modest $\langle f_{\rm esc} \rangle = 5$ per cent still requires a cut-off at magnitudes brighter than $M_{\rm UV} \approx -12$ given the higher $\xi_{\rm ion}$ from *JWST*. These faint $M_{\rm UV}$ have not been statistically probed yet by *JWST* observations, but upcoming ultra-deep imaging of a gravitationally lensed cluster (the Glimpse programme, PI: Atek, *JWST* ID: 3293) will measure $\xi_{\rm ion}$ and $\beta_{\rm UV}$ from lensed star-forming galaxies down to $M_{\rm UV} \approx -12$. Deeper measurements of analogues at moderate z are also critical to examine how well the $f_{\rm esc}$–$\beta_{\rm UV}$ relation holds at fainter magnitudes (and bluer objects), as well as higher z, pushing as close as possible to the epoch of reionization.

(iii) What about the faint end of the UVLF? The slope and turnover magnitude remain as the key uncertainties of this observable. For a turnover to match reionization measurements, it would have to be at a bright $M_{\rm UV} \approx -17$, as illustrated in Fig. 3, far above the current UVLF limits. An alternative is a shallow faint-end slope. We have repeated our analysis with the Finkelstein & Bagley (2022) UVLF, which assumes a double power-law functional form with a flattening towards the faint end, and found that the tension persists (see Appendix A in the supporting information). This is not surprising, as the tension in Fig. 2 requires little to no extrapolation of the UVLFs during reionization (down to $M_{\rm UV} \approx -15$, where the faint-end uncertainties affect galaxy abundances at the 30 per cent level). If a turnover or flattening of the UVLF was the solution, it would be of paramount importance to understand its physical origin, whether it is due to feedback during reionization (Shapiro et al. 2004) or an exotic cosmology (Sabti, Muñoz & Blas 2022).

(iv) Maybe our theoretical models are wrong? The main uncertainty is how many recombinations take place, which we have modelled through a simple clumping factor C. Past work has suggested that additional recombinations can explain an extended reionization history inferred from the Lyman-α forest at $z \sim 5$–6 (Davies et al. 2021; Qin et al. 2021). Such a 'tax on the rich' (in terms of ionizing photons; Furlanetto & Oh 2005) could alleviate the budget crisis. As a test, we show in Fig. 3 how even a large $C = 20$ – implying nearly an order of magnitude more recombinations throughout all of reionization – does not suffice to harmonize galaxy and CMB observations, still overproducing reionization (more than 3σ above $\tau_{\rm CMB}$ measurements). Of course, we expect the process of reionization to be complex and inhomogeneous, but we note that these many recombinations per hydrogen atom are not standard in ΛCDM cosmologies (even including mini-haloes; Gnedin 2024), and could point to additional baryon fluctuations at very small scales, or missing ingredients in our theories.

Fig. 3 summarizes how different possible solutions would affect the timing of reionization. While these scenarios can be re-calibrated to produce the correct $\tau_{\rm CMB}$ (e.g. increasing $M_{\rm UV}^{\rm ion.\,cut\text{-}off}$ or decreasing $f_{\rm esc}$), measurements of $x_{\rm H\,I}(z)$ can potentially distinguish between them, as posing a cut-off $M_{\rm UV}^{\rm ion.\,cut\text{-}off}$ makes reionization faster (like oligarchic models; Naidu et al. 2020), whereas decreasing $f_{\rm esc}$ slows it down (appearing democratic; F19). Of course, a z-dependent $f_{\rm esc}$ can mimic this effect, so clustering measurements of reionization bubbles, for instance with the 21-cm line (Furlanetto, Zaldarriaga & Hernquist 2004; Muñoz et al. 2022), will be required to break degeneracies. We emphasize that each of the mechanisms invoked in this section requires giving up the constraints from at least one of our galaxy measurements, be it the UVLFs, $\xi_{\rm ion}$, $f_{\rm esc}$, or a combination of them. Further observations of galaxies, $x_{\rm H\,I}$, and $\tau_{\rm CMB}$ will sharpen our understanding of the reionization process, as current error bars are still sizeable and may hide underlying systematics. While the list presented here is not exhaustive, we hope that it encourages theoretical and observational work to resolve the *JWST* photon budget crisis.

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5 CONCLUSIONS

The launch of *JWST* is allowing us to directly access the properties of the first galaxies with unprecedented sensitivity. Early observations are showing that early, faint galaxies are prolific producers of ionizing photons. Here, we have combined new *JWST* measurements with determinations of the escape fractions $f_{\rm esc}$ of reionization-era analogues to show that our current galaxy observations predict a process of reionization that ends too early. That is, the situation has been reversed from the *WMAP* era, where the concern was producing *enough photons* to match $\tau_{\rm CMB}$, to the post-*Planck* and *JWST* era, where there may be *too many photons*.

To match the CMB optical depth, the $\dot{n}_{\rm ion}$ of early galaxies must dramatically decrease. This is currently *not* observed in the high-z galaxy population. For instance, the UVLFs do not show a significant turnover down to $M_{\rm UV} \approx -15$ (Atek et al. 2018), faint galaxies during the epoch of reionization are very blue down to $M_{\rm UV} \approx -17$ (hinting at high $f_{\rm esc}$; Topping et al. 2022; Cullen et al. 2023), and, on average, galaxies produce significantly more ionizing photons than inferred from *HST* + *Spitzer* observations down to $M_{\rm UV} \approx -15$ (Atek et al. 2024; Endsley et al. 2024; Simmonds et al. 2024). As such, taken at face value the galaxies *JWST* has observed already produce enough ionizing photons to reionize the universe. This does not include faint galaxies still unprobed by *JWST* observations, or a contribution from early black holes (which appear prevalent in early *JWST* observations; Matthee et al. 2024). There must be a missing ingredient in either our modelling or observations to harmonize the galaxy and CMB inferences of reionization.

Moving forward, there are several avenues that can further audit the ionizing-photon budget. Future CMB surveys are expected to measure $\tau_{\rm CMB}$ to $\approx$0.002 (Allys et al. 2023), which would sharpen our understanding of reionization. Better constraints on the timing of reionization beyond $\tau_{\rm CMB}$ (e.g. via the kinematic Sunyaev–Zel'dovich effect and the transmission of Lyman-α photons from high-redshift sources; Ouchi, Ono & Shibuya 2020; Chen et al. 2024; Lu et al. 2024; Nakane et al. 2024; Raghunathan et al. 2024) and tomographic measurements of the distribution of neutral and ionized hydrogen through the 21-cm line (Morales & Wyithe 2010; Abdurashidova et al. 2022) will provide invaluable information on how different sources contribute to the photon budget. Further studies of both $f_{\rm esc}$ (at low z) and $\xi_{\rm ion}$ (at high z) are critical to account for selection biases in our samples, or for missed assumptions in their interpretation. The biggest theoretical uncertainty is quantifying the recombination rate, which has a substantial effect on the reionization history (see Fig. 3) and may alleviate the requirements on the sources. In particular, it is crucial to understand how an increase in the recombination rate at $z \sim 6$ due to dense IGM clumps would carry over to higher redshifts, during the bulk of reionization.

In summary, recent observations have found that early galaxies were numerous, efficient producers of ionizing photons, and likely to have non-negligible escape fractions. Together, these galaxy observations imply an excess in the ionizing-photon budget during reionization, which would end this cosmic epoch earlier than allowed by CMB data. The *JWST* era has just begun, and here we have examined how future observations and theoretical efforts can shed light on this tension. As of the time of writing, the different solutions are in conflict with at least one observational constraint. Resolving this tension on reionization is a key step to finally understanding the last major phase transition of our universe.

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Software: NUMPY (van der Walt, Colbert & Varoquaux 2011), SCIPY (Jones, Oliphant & Peterson 2001), MATPLOTLIB (Hunter 2007), ZEUS21 (Muñoz 2023), and CLASS (Blas, Lesgourgues & Tram 2011).

DATA AVAILABILITY

The data underlying this letter will be shared on reasonable request to the author.

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SUPPORTING INFORMATION

Supplementary data are available at *MNRASL* online.

appendix_PhotonOverproduction

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